

DOT Ground Laser Receiver: Overview and Major Trades

Kevin M. Birnbaum,* Jeffrey R. Charles,* William H. Farr,* Jonathan Gin,*
Kevin J. Quirk,* William T. Roberts,* Jeffrey A. Stern,† and Yen-Hung Wu‡

The Deep-space Optical Terminals (DOT) project will provide high-data-rate optical communications from planetary distances. An overview of the architecture of the ground-based receiver subsystem is presented, along with a conceptual design of the subsystem assemblies. Major trades are described along with the selected approach.

I. Introduction

Optical communications has the potential to increase the achievable data rate from spacecraft at planetary distances by orders of magnitude [1,2,3]. The Deep-space Optical Terminals (DOT) project is intended to be the first demonstration of bidirectional optical communications between Earth and deep space [4]. The top-level requirement is to deliver more than 10 times the data rate of a link-limited state-of-the-art Ka-band system [5] with comparable mass and power burden on the host spacecraft.

The DOT system is composed of four major subsystems, as shown in Figure 1. The DOT Mission Operations Center (MOC) controls DOT operations and performs data analysis and archiving. The Ground Laser Transmitter (GLT) sends an uplink beam to the spacecraft [6]. This beam is used as a pointing reference (i.e., beacon) at the spacecraft, as well as carrying uplink communication data. The Flight Laser Transceiver (FLT) is the DOT subsystem mounted on the spacecraft [7]. It receives the uplink beam and transmits a downlink beam. The Ground Laser Receiver (GLR) receives the downlink light and recovers the communication data. DOT also supports ranging by measuring the time of flight on both the uplink and downlink beam.

An overview of the DOT requirements is given in [4]. In order to perform all of the required demonstrations, the DOT system specifies two sets of requirements on the GLR corresponding to two modes of operation: a high-rate mode and a low-rate mode. The high-rate mode, which is used only for nighttime operations, must provide a net gain of 142 dB to support the maximum DOT downlink data rate of 267 Mb/s. The low-rate mode is used to demonstrate link acquisition over a range of conditions, including Sun–Earth–probe (SEP) angles

* Communications Architectures and Research Section.

† Instrument Electronics and Sensors Section.

‡ Optics Section.

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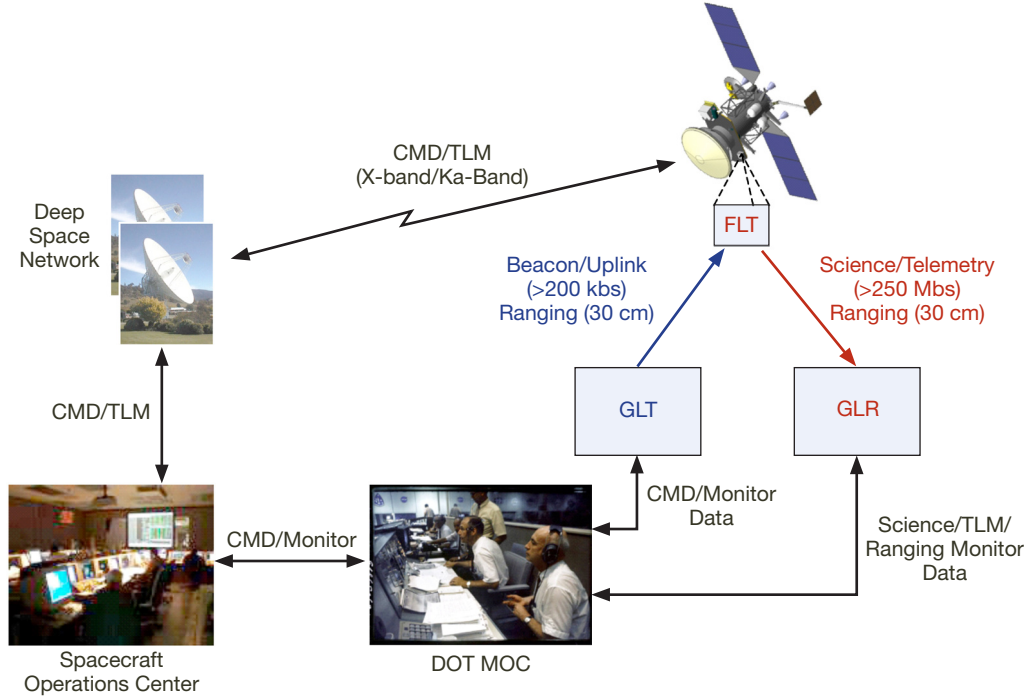


Figure 1. The architecture of the DOT system. The GLR accepts the downlink light from the FLT and sends the decoded data to the DOT MOC.

down to 5 deg. In the low-rate mode, the net gain need only be 124 dB. In our trades, discussed in more detail in Section II, we considered both using a single set of hardware to meet all requirements, as well as using different equipment for each mode of operation.

There are four major factors that drive the design of the GLR subsystem. The first is the large net gain requirement. This drives the use of a large collecting area, as well as highly efficient optics and detectors for receiving the faint signal from deep space. The second factor is the requirement for daytime and low SEP angle operations. This is unusual for telescopes, which are typically designed to operate only at night (or in the case of solar telescopes, only while pointing directly at the Sun). The third factor is the low rate of signal photons. The link operates in the photon-starved regime, which necessitates the use of efficient modulation and error-correcting codes to maximize the bits per photon [8]. This ultimately impacts the electronics used to receive and decode the downlink signal. The fourth factor is the low ratio of signal photons to background photons. The detected rate of background photons may exceed the rate of signal photons by as much as 18 dB during low SEP operations. This increases the difficulty of performing spatial and temporal acquisition of the signal. It also makes it necessary to precisely filter the incoming light to keep the background rate as low as possible while minimizing the loss of the signal photons.

The reference architecture of the GLR is shown in Figure 2. There are six assemblies in the GLR subsystem. The *telescope assembly* collects and concentrates the downlink light coming from the FLT. The *aft optics assembly* takes the light from the telescope assembly and filters out the background light. It also provides functions for beam monitoring and alignment. The downlink light is then coupled to the *detector assembly*, where the photons are convert-

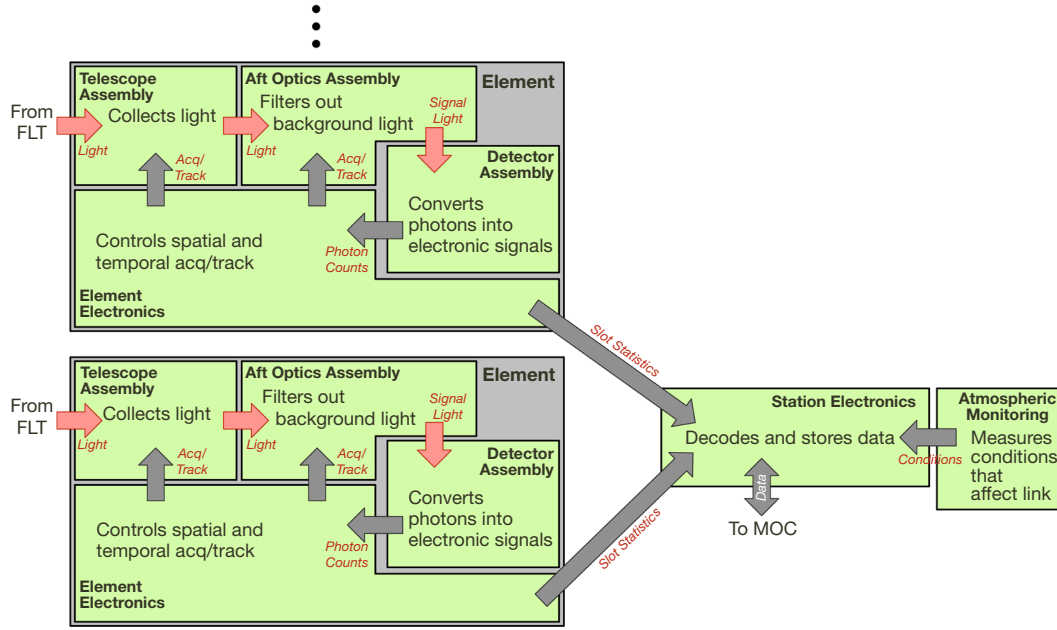


Figure 2. The architecture of the GLR. The assemblies within the GLR subsystem are represented by green boxes. Four of the six assemblies are repeated in each element (shown in gray) of the array, whereas the remaining two are shared by all elements. An array of two elements is shown, but one or more may be used.

ed into an electronic signal. The detector assembly must distinguish between photons striking different regions of the focal plane, in order to provide the tracking information used to stabilize the optical line of sight. The electronic signals from the detector assembly are sent to the *element electronics*, which synchronizes to the downlink signaling format and estimates the signal and background photo-count rates. It provides the control signals to the telescope assembly and aft optics assembly, which are used to acquire and track the downlink light. The slot statistics (which may be represented as the number of photo-counts in each time interval of the downlink signal structure) are sent from the element electronics to the *station electronics*. The station electronics uses the synchronized slot statistics to decode the information that was transmitted over the downlink; it then stores the resulting data for eventual relay back to the DOT MOC. The station electronics also relays to the DOT MOC the atmospheric conditions that affect the link, such as sky radiance, atmospheric attenuation, and turbulence. These parameters are measured by an *atmospheric monitoring assembly*. The atmospheric monitoring assembly is based on a suite of previously developed instruments [9–16], many of which are in operation at NASA's Table Mountain Facility or Goldstone Deep Space Communications Complex.

As shown in Figure 2, the telescope assembly, aft optics assembly, detector assembly, and element electronics may be grouped into an element. Multiple elements may be combined in an array within the GLR. The net gain of the GLR is approximately the sum of the net gain of the elements (minus the losses in decoding). Any number of elements may be used. However, in this architecture each element must be capable of performing signal acquisition and tracking independently. This imposes a lower limit on the gain of each element, given the link conditions [17]. Note that the signals are combined electronically after they have

been detected and synchronized, so that complicated beam combiners or pathlength equalizers are not needed.

We will now discuss the trades and baseline conceptual design of these assemblies in more detail. The telescope assembly is treated in Section II; the aft optics assembly is in Section III; the detector assembly is in Section IV; and the element electronics and station electronics are in Section V.

II. Telescope Assembly

The telescope assembly points to the FLT and collects the downlink light. The requirement for a large net gain in the GLR flows down to a requirement for a large collecting area in the telescope assembly. After allocations are made for optical losses, the requirement of 142 dB (124 dB) gain in the GLR is used to derive a requirement of 110 m² (3.8 m²) collecting area in the high-rate (low-rate) mode, corresponding to an equivalent diameter of 11.8 m (2.2 m).

There are multiple approaches to the acquisition of the telescope assembly: renting existing facilities (possibly with some modification), building a new facility, or a combination of renting a facility for one mode of operation and building a facility for the other.

First we discuss the options for renting existing facilities. We identified three candidate facilities with sufficient collecting area for the high-rate mode: the Very Large Telescope (VLT) when at least three of its four 8.2-m telescopes are used in an array; the Keck Observatory when both of its 10-m telescopes are used; and the Large Binocular Telescope (LBT). The VLT, located in the Atacama Desert of Chile and operated by the European Southern Observatory, would pose a number of logistic problems. For example, its location makes it impossible to demonstrate long link durations with a GLT located in the United States. Of the other two candidates, the LBT has the advantage of a lower cost per night of operation and a location in the southwestern continental United States. This location is favorable since it allows the use of existing facilities for the GLT.

The LBT, located on Mount Graham, Arizona, consists of twin 8.4-m Gregorian telescopes attached to a single altitude–azimuth mount. Each telescope may be used in one GLR element, eliminating the need for optical combining of the two. The LBT facility could be used by packaging the aft optics assembly and detector assembly into visitor instruments that are mounted at focal stations of the twin telescopes. The LBT meets all requirements for use as the telescope assembly in high-rate mode. However, the LBT cannot meet (and cannot reasonably be modified to meet) the 5-deg SEP angle requirement of the low-rate mode.¹

Next we consider existing telescope facilities that may be used for the low-rate mode. We did not identify any existing telescopes with ≥ 2.2 -m aperture that currently may operate

¹ Tom McMahon, "Use of Large Binocular Telescope as Ground Lasercom Receiver Demonstrator," JPL Subcontract No. 1400570 (internal document).

while pointing at 5 deg from the Sun. However, some telescope facilities may be modified to allow near-Sun operations. The Hale Telescope, a 5-m telescope on Palomar Mountain, California, has a 42-m dome. With modification to the dome opening and additional baffling, the Hale Telescope could provide sufficient collecting area while pointing near the Sun [18]. The cost of modifications, however, is higher than other options discussed below. The Hooker Telescope, a 2.5-m telescope on Mount Wilson, California, is another telescope that may be baffled to allow near-Sun pointing. The optics of the Hooker Telescope, though, are temperature sensitive and have a long time constant for thermal relaxation. There is a significant risk that the telescope point-spread function would be too large to allow enough background light rejection when the telescope is operated during the day and across day–night transitions.

We turn now to the options for building a new facility to serve as the telescope assembly. A new facility could be constructed to meet both the high-rate and low-rate requirements. Such a facility would feed forward beyond the DOT demonstrations, as it could be used in the eventual operations of deep-space optical communications.

Except for the near-Sun pointing capability, the requirements on the telescope assembly are very relaxed compared to most astronomical telescopes. For example, the image spot size of the telescope may be up to 20 μrad (depending on the atmospheric seeing at the telescope site), which is much larger than the diffraction-limited performance commonly demanded of astronomical instruments. Furthermore, the field of view of the telescope can be as small as 50 μrad , as the telescope must only collect light from a single point source. That source is also monochromatic, whereas astronomical telescopes are typically designed to accommodate a wide range of wavelengths. These factors led us to consider approaches to the telescope design that give a much lower cost compared to an astronomical telescope of the same diameter.

With these considerations in mind, a number of point designs for low-cost telescopes were created. Since a number of smaller telescopes may be combined to form an array (as discussed in Section I), the figure of merit is taken to be the cost of a telescope assembly divided by its effective area of light collection. Note that the cost of the telescope assembly includes not only the cost of the telescope optics, but also the mounts, gimbal, dome, site preparation work, etc. The relative figures of merit of the point designs are shown in Figure 3.

We consider two broad types of designs: those based on a monolithic primary mirror and those based on a segmented primary mirror. Monolithic designs with primary diameters between 0.8 m and 8.2 m have been investigated. We have found that there is a knee in the cost curve for these designs, such that the cost per area is nearly constant for apertures below 2.2 m. Above this diameter, the cost per area increases nearly proportional to diameter. These results are consistent with the “conventional wisdom” that telescope costs scale between $\propto D^2$ and $\propto D^3$, depending on the design regime [19,20]. Based on this analysis, if a monolithic primary design is chosen, then the lowest cost build approach that meets requirements is an array of 2.2-m terminals.

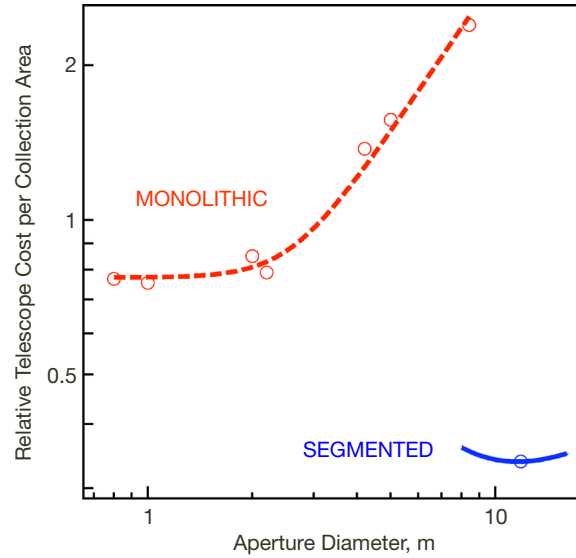


Figure 3. The relative cost of building a telescope assembly per collecting area (in arbitrary units) vs. diameter of the collecting aperture. Circles indicate point designs, while smooth curves are based on parametric scaling. The dashed red curve is a fit to the point designs based on a monolithic primary mirror. The solid blue curve is based on the segmented mirror point design, with parametric scaling of each of its major components.

We also investigated an approach to the telescope assembly based on a large segmented primary.² The relatively modest requirements on spot size and field of view allow significant cost savings, comparable to those found in the Hobby-Eberly Telescope [21]. A conceptual point design was created to meet the GLR requirements with a single telescope. Parametric scaling of the cost of each major telescope component (e.g., primary mirror, dome, gimbal, etc.) was used to estimate the cost as a function of telescope diameter. The 12-m telescope design is near the minimum of the cost curve, though the minimum is shallow. The design could be scaled up or down by 50 percent in area with negligible impact on the cost per area.

There are a number of factors to consider when comparing the telescope assembly design based on the monolithic 2.2-m and the segmented 12-m. An array of 2.2-m telescopes (29 would be required to meet the total collecting area requirement) has the advantage of graceful degradation, as failure of any element would only reduce the signal by 3 percent. Similarly, this design could easily be made more robust by adding additional elements to introduce redundancy. Finally, there could be programmatic advantages to building the array slowly over time, with a limited capability available at intermediate steps along the way. On the other hand, the single-aperture approach has the advantage that it can acquire signals at a lower irradiance, enabling future missions at farther ranges or with lower-mass and lower-power flight terminals. Furthermore, the single-aperture approach has much lower build costs and costs for maintenance and operations. Therefore, of the build options, the approach based on the single segmented aperture is considered most favorable.

² Thomas A. Sebring, "A Study to Illustrate the Concept and Likely Cost for a 12-Meter-Aperture Ground-Based Telescope for Laser Communications," JPL Subcontract No. 1400382 (internal document).

Finally, we consider the option of using a combination of existing facilities along with new facilities to meet the DOT requirements. This approach would use the LBT to satisfy the high-rate requirements, while building a new telescope for the low-rate mode of operation. This eliminates the costs and risks of attempting to modify an existing telescope to point near the Sun, while avoiding the high cost of building a large-area telescope. To minimize costs, the new telescope would have the minimum aperture of 2.2 m. Beyond the DOT demonstrations, this new telescope would also provide an operational capability for bidirectional communication to spacecraft in geosynchronous orbits, at the Moon, or at the Lagrange points. The telescope could also be adapted to serve as an uplink station for deep space.

Based on the DOT project goals, including minimizing cost and risk, as well as providing feed forward to future capabilities, the baseline approach chosen was that of renting the LBT and building a new 2.2-m telescope with near-Sun pointing capability. For the initial operational capability, after successful demonstrations of the DOT terminals, we recommend pursuing the ground receiver approach based on a large segmented primary mirror telescope.

III. Aft Optics Assembly

The aft optics assembly relays the signal light from the telescope assembly to the detector assembly while rejecting the background light. It filters the light by controlling the allowed polarization, wavelength, and spatial mode.

The primary trade in the design of the aft optics assembly is the choice of technology for spectral filtering. The spectral filter needs to have a high efficiency at the desired wavelength and a narrow bandwidth (noise equivalent bandwidth ≤ 0.17 nm), and accept a large etendue. The etendue is the product of the area and solid angle of the rays crossing a plane, and is invariant throughout the optical system. The etendue of the GLR system is 3.9×10^{-8} m²sr in the high-rate mode.

There are three candidate approaches for the spectral filter. The first is an optic with a multilayer dielectric coating. Optical bandpass filters are commonly made this way, but this approach does not work efficiently for the extremely narrow passband required. The second approach is an etalon filter, based on two parallel flat reflectors. This technique can achieve the required bandwidth, but has a number of drawbacks, including poor out-of-band rejection, relatively low peak transmission, high angular selectivity (requiring a large filter to meet the etendue requirement), and high sensitivity to thermal and mechanical disturbances. The third approach is based on a reflective volume Bragg grating (VBG) [22,23]. This is a bulk piece of glass that has been patterned with an index of refraction that varies periodically in the direction of propagation. It is highly reflective at the filter wavelength and highly transmissive at other wavelengths. The filter wavelength can be adjusted through thermal tuning. The VBG was selected for the baseline design because of its narrow bandwidth, large acceptance angle (permitting a design with a large etendue with small optics), and high efficiency.

The architecture of the aft optics assembly is shown in Figure 4. The light from the telescope assembly passes through a coarse field stop. This stop does not define the field of view, but is simply used to reduce the stray light entering the system. The light is then collimated and passed through a coarse dual bandpass filter. One passband is at the signal wavelength, and the other is at a visible wavelength for alignment light. The light then reflects off a fine steering mirror placed at a pupil plane. This mirror is controlled by the element electronics to compensate for pointing errors in the telescope assembly. The light is then refocused. A dichroic splitter is used to divert the alignment light to a separate camera. This dichroic optic, though highly transmissive at the signal wavelength, can also be used to couple in light from a fiber injection port. The transmitted signal light comes to a focus on an adjustable fine field stop, which defines the field of view of the system. The light is then collimated and sent through a quarter-wave plate and a half-wave plate, each on an independent rotation stage. This combination allows any polarization of light to be converted to any desired linear state. The light continues on to a polarizing beam splitter. The signal light passes through, while the portion of the background light in the orthogonal polarization is diverted to a power meter via a baffled path. The signal light then passes through a quarter-wave plate (whose axes are set at 45 deg) and strikes the VBG. The light outside the spectral band passes through the grating and goes along a baffled path to another power meter. The signal light reflects off of the grating and returns through the quarter-wave plate. The linear polarization is rotated through 90 deg by the two passes through the quarter-wave plate, so the light now reflects off of the polarizing beam splitter. It continues on to a rotatable linear polarizer, used to attenuate the beam during testing and calibration. The light then passes through a rotatable half-wave plate and strikes another polarizing beam splitter. This combination makes effectively a splitter with a variable ratio of transmis-

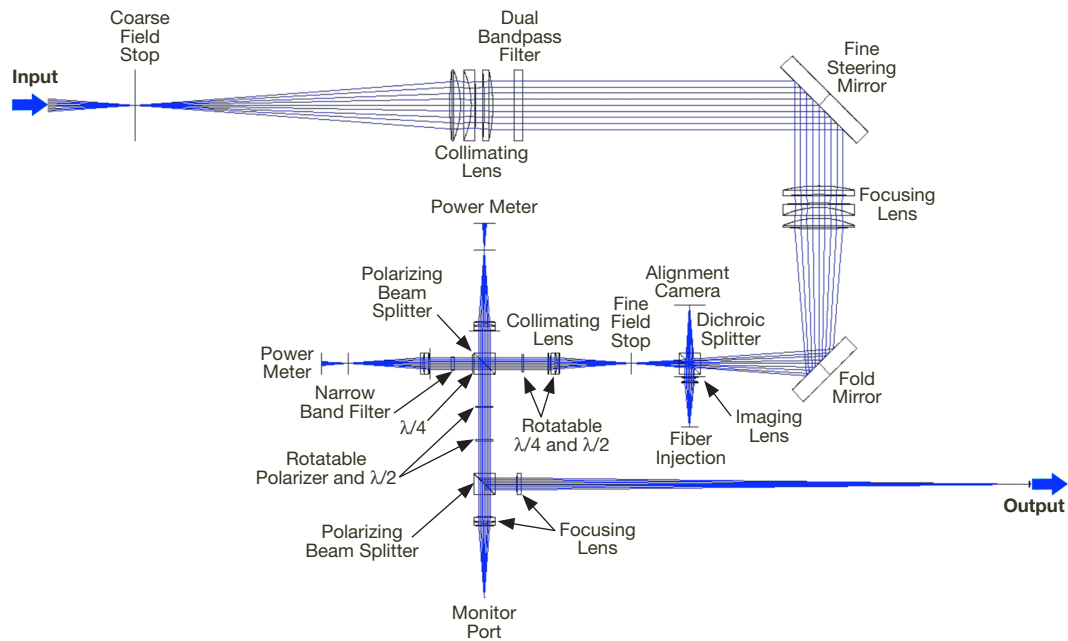


Figure 4. The architecture of the aft optics assembly. The path marked “Input” comes from the telescope assembly, and the path marked “Output” goes to the detector assembly. The optic labeled “Dual Bandpass Filter” transmits light at the signal wavelength and at a visible wavelength used for alignment. The cube marked “Dichroic Splitter” transmits the signal wavelength and reflects the alignment wavelength.

sion to reflection. This is used to divert a controlled fraction of the light to a monitor port, used during testing and calibration. The light finally exits the aft optics assembly and enters the detector assembly.

This architecture has a number of beneficial features. It provides several ports for checking the spatial, polarization, and spectral profile of the input light. It has a port for injecting a known test signal light. It has multiple stages of filtering and can be baffled to minimize stray light. Additionally, this design can be adapted for use with different telescope assemblies simply by changing lenses.

IV. Detector Assembly

The detector assembly takes the light from the aft optics assembly and converts the photons into an electronic signal. The driving requirements for the detector assembly are detection efficiency >50 percent; dark count rate <330 kHz; timing jitter <120 ps; and etendue $>3.9 \times 10^{-8} \text{ m}^2\text{sr}$. The etendue requirement can be converted to a requirement on area given the maximum angle of incidence for efficient detection. For example, a 274- μm -diameter circular detector that detects light up to 27 deg ($f/1$ beam) would meet the requirement.

The detector must have an array format. A minimum of three pixels must be spatially separated in the focal plane, so that a feedback signal can be extracted for tracking the line of sight to the FLT. Furthermore, the high required etendue can only be achieved by arraying many pixels, given current technological limitations. Finally, spreading the light over many pixels is required in order to avoid blocking losses due to the saturation of each pixel, given the high count rates expected in the link. This last factor, however, is less stressing than the high etendue requirement for the technologies under consideration.

The major trade in the detector assembly is the choice of detector technology. Table 1 shows some of the candidate technologies for detection of light at the downlink wavelength of 1550 nm. As shown in Table 1, no existing, demonstrated detector system presently meets the GLR requirements.

The superconducting nanowire single-photon detectors (SNSPDs) offer the best combination of high timing resolution, high saturation rate, and high detection efficiency [24,25]; individual pixels and small arrays have demonstrated the required performance characteristics. However, the small pixel sizes imply that arrays of several hundred elements are needed to meet GLR requirements. Thus, technology development and significant cryogenic engineering will be needed to create the required large-format arrays.

The InGaAs devices are available in large arrays with sufficient collecting area [26]. However, the performance of each pixel does not meet requirements. In particular, the timing jitter is too high. Low jitter has been demonstrated in single-pixel InGaAs devices [27], but only under conditions where the dark count rate was unacceptably high.

The intensified photodiode (IPD) is a relatively mature technology that meets nearly all requirements [28]. The only limitation is the low detection efficiency of 30 percent at 1550 nm.

Table 1. The detector technology trade table. Performance is color-coded, with green most favorable and red least favorable.

Technology→	Downlink Wavelength: 1550 nm								
	Geiger Mode		NAF	InGaAs Photocathode		Linear		Superconducting	
	Ge	InGaAs	InGaAs	PMT ^[1]	IPD ^[2]	InGaAs	HgCdTe	Nanowire	TES ^[3]
Detection Efficiency @ 1550 nm	15%	45%	23%	15%	30%	8%		60%	90%
Dark Rate/mm ²									
Timing Resolution (1 sigma)		270 ps	240 ps	1000 ps	90 ps			50 ps	
Pixel Area				>1 mm dia	>1 mm dia			100 μm^2	
Operating Temperature	80–180 K	~220 K	~220 K	220 K	200–300 K	200–300 K	80K	<4 K	<0.3 K
Array Size (To Date)	1	256×256	8×8	16	52	>128×128	>128×128	4×4	
TRL ^[4] for GLR	2	2	2	2	6	2	2	4	2
Can Meet Requirements?	No	No	No	No	No	No	No	Maybe	No

^[1] PMT = photomultiplier tube

^[2] IPD = intensified photodiode

^[3] TES = transition-edge sensor

^[4] TRL = technology readiness level

Based on this state of the art, the baseline concept of the GLR is to develop large arrays of SNSPDs for the GLR detector assembly. The InGaAs photon counting arrays will continue to be considered as an alternative as technology development improves the timing resolution. The IPD will be kept as a low-risk backup option; however, meeting GLR requirements using the IPD-based detector assembly will require a larger collecting area in the telescope assembly. The backup option would use the Keck Telescopes instead of the LBT to meet the GLR requirements.

The development of large SNSPD arrays will require several issues to be addressed. The yield of individual pixels will need to be increased in order to achieve the required high average detection efficiency. A closed-cycle cryostat operating at ~3 K will need to be engineered; it must support efficient free-space coupling, and must be able to feed the hundreds of high-bandwidth signals to room temperature. This will likely require cryogenic front-end processing (pixel combination) to reduce the number of wires, and hence thermal conductance, from room temperature to 3 K. Another area of development is bias control and monitoring for the large arrays. Relative propagation delays across the array will also need to be addressed. The array will also require a precisely aligned microlens array to create a high equivalent fill factor.

V. Electronics Assemblies

The element electronics accepts the electronic signal from each detected region of the focal plane. It determines the number of photons received in each temporal slot in each region. It synchronizes to the downlink signal, and estimates the rate of signal and background photons. The element electronics also controls the acquisition and tracking of the downlink. The station electronics decodes the telemetry data based on the synchronized slot

statistics from the element electronics. The electronics assemblies also provide monitor and control functions for the GLR.

The electronics are allocated 1.5 dB implementation loss, in addition to the 1.2 dB gap to capacity for the serially concatenated pulse-position modulation (SCPPM) code [8]. The electronics must meet this requirement across the full range of signaling parameters [4], including all operating points from 13 kb/s to 267 Mb/s. The signaling format has variable PPM orders, code rates, slot widths, and symbol repetitions to cover the wide range of signal and background photon rates. The electronics must be flexible enough to reconfigure to any operating point within 5 min.

The major trade in the electronics is the choice of whether to use commercial off-the-shelf (COTS) hardware or custom hardware. COTS products were the basis for the planned Mars Laser Communications Demonstration (MLCD) Project [29,30], which used similar signaling but at much lower data rates. The COTS platform, however, still required development of custom interfaces. It was also found to be more expensive to maintain than an internally developed platform because of the short life cycle of the commercial products. A custom hardware platform was developed under a NASA Interplanetary Network Directorate (IND) technology program to fill the needs for reception of high-rate optical communications signals from deep space. These products, which have been successfully demonstrated in emulated links [31], are the best match to the DOT GLR requirements and were selected for the baseline approach.

The architecture of the GLR electronics is shown in Figure 6. This architecture is scalable to data rates over 1 Gb/s, and accommodates both a single-element or arrayed architecture for the GLR. There are six major subassemblies shown in the figure: the programmable oscillator, receiver, channel combiner, and signal acq/track controller within the element electronics; and the channel combiner/de-interleaver and decoder in the station electronics.

The programmable oscillator is a frequency synthesizer with an output phase that tracks an arbitrary function. It is used to compensate for the time-base distortion between the spacecraft and the ground station, based on the predicted Doppler profile. It accepts reference frequency and time from the station and sends the synthesized frequency to the receivers.

The receiver samples the output of the photon-counting detector, synchronizes to it, and performs estimation of the signal and background rates. It uses a custom mixed-signal (RF/digital) offset phase-locked-loop circuit to control the phase of the clock that samples the photon-counting detector output. Precise placement of the position of the sample times facilitates synchronization and detection without the use of multiple samples per slot, enabling slot rates up to 6.4 GHz. Each receiver has 10 Gb/s of input/output (I/O) bandwidth over standard fiber optics, which it uses to send the synchronized slot statistics and estimates to the channel combiner.

The channel combiner is used to combine the synchronized receiver outputs prior to information decoding. Each channel combiner has 20 Gb/s I/O over fiber optic connections. Channel combiners may be replicated and connected in a tree to combine an arbitrary number of receivers.

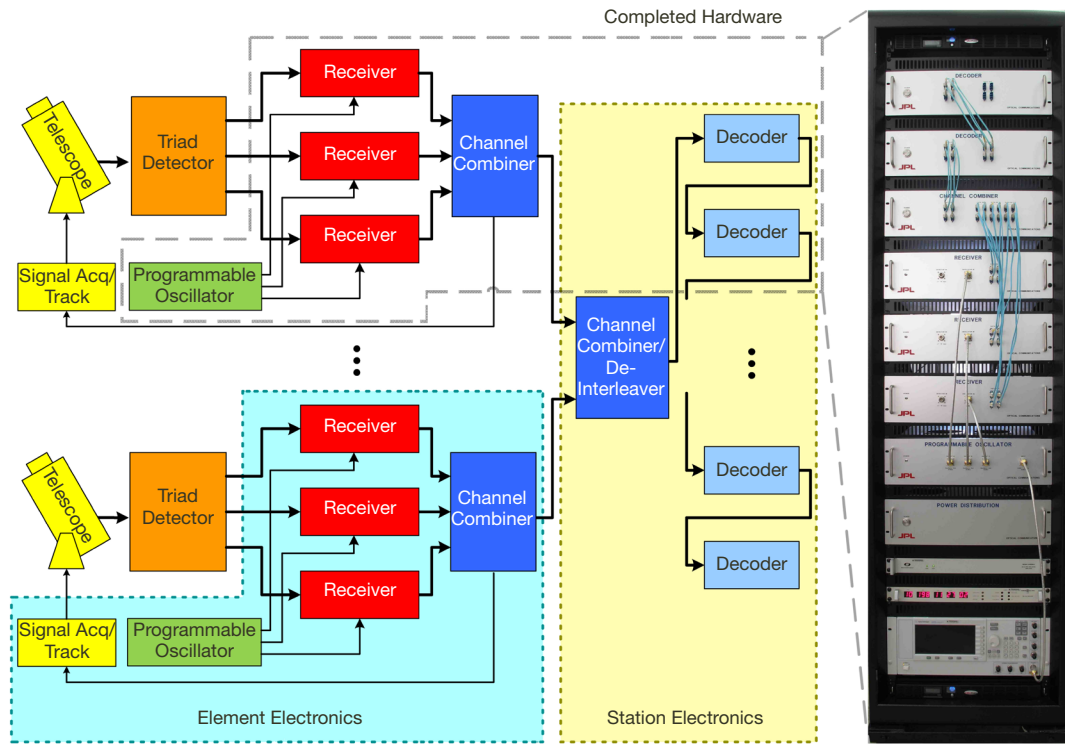


Figure 6. The architecture of the GLR electronics. The subassemblies in the dashed box have been built and are shown on the right. Two elements of a GLR array are shown. The subassemblies belonging to one instance of the element electronics are shown in the dotted box on the lower left; those belonging to the station electronics are shown in the dotted box in the center. Three receivers are shown for each detector, assuming the detector is partitioned into three parts, with each part connected to one receiver. The ratio of signal intensity on each part of the detector is used by the signal acq/track controller to feed back to the telescope pointing. The decoders are connected in a chain, with a length that can be increased in order to accommodate a higher data rate.

The channel combiner on each element of the GLR array passes the signal photon flux estimates to the signal acq/track controller. The latter subassembly controls the acquisition and tracking of the signal light by adjusting the pointing of the telescope assembly and aft optics assembly. This architecture is based on a detector that is divided into at least three regions in the focal plane, with each detector region connected to a receiver. The receiver estimates the signal flux detected in that region, and the signal acq/track controller uses the map of signal flux across the regions to compute a centroid. The signal acq/track controller also controls the spectral filter wavelength, field stop size, and state of polarization in the aft optics assembly, which it adjusts to maximize the signal margin in the link.

The final channel combiner in the tree also functions as a de-interleaver. Interleaving is used in the signaling format to mitigate the effect of fading in the link. The de-interleaver will be implemented on a daughter card with a large memory (>2 GB), which will plug in to the existing channel combiner board.

The de-interleaved data are then sent to a chain of decoders. The decoders have a scalable architecture, allowing an arbitrary number of decoder cores to be implemented by extending the chain. Each decoder accepts encoded data if it is idle, or passes it down the chain if

it is busy. The decoded bits from each decoder are packetized, aggregated across a network, and restored to their original ordering. Using the current SCPPM decoder core with four iterations per codeword, each decoder can process ~150 Mb/s. The decoder has 20 Gb/s I/O over fiber. A centralized server accepts the decoded data frames over gigabit Ethernet via User Datagram Protocol/Internet Protocol (UDP/IP) and performs the reordering.

The electronics subassemblies accept standard interfaces for time and frequency distribution. The master time for the station is set by a commercial reference source, such as a GPS-disciplined crystal oscillator. Commercial time-code generators and translators are used to transfer time from the station to each element. Precise comparison of the received clock on the downlink signal to the station time is used in computation of the range to the spacecraft.

Each subassembly also supports monitor and control through a gigabit Ethernet interface. A custom graphical user interface (GUI) has been created for monitor and control, data logging, and system characterization, with modules created for the receiver and decoder. Additional modules will be developed and integrated to provide a unified interface.

VI. Conclusion

Trades were performed for each assembly within the GLR, and the selections led to a baseline concept. This concept uses the LBT to support the high-rate mode of operation, and builds a new 2.2-m telescope with near-Sun pointing capability for the low-rate mode. The concept uses a common design in the optics behind the telescope, using a narrow spectral filter based on VBG technology and standard components. The downlink signal light is detected by SNSPDs, which will require new technology development. The electronics, firmware, and software are based on products previously developed under a NASA technology program. Except for the photon-counting detector array of the required size, all of the technology is currently available. A backup option using only existing technology (based on the IPD detector and the Keck Telescopes) was also identified. All DOT requirements can be met, and a plan and schedule have been drafted for completing the GLR to support a flight system launching in 2018.

While addressing the requirements for DOT, we have also identified a path forward to an operational capability. The GLR concept is scalable to greater ranges or higher data rates. The architecture allows higher gain to be achieved by arraying receiver elements. Large segmented telescopes have been identified as a low-cost approach to the large collecting area needed for deep-space receivers. We have baselined technology development of large arrays of superconducting photon counting detectors, which have demonstrated high efficiency in single devices. The electronics are based on a scalable architecture to support higher data rates and larger arrays. Together, these concepts will enable unprecedented data rates from planetary distances, which will allow more scientific data to be returned, enhancing the value of each mission that uses optical communications.

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